

Optimal Choice of Material for HEB Superconducting Mixers

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Abstract—We demonstrate that a potential distinction in ultimate performance of phonon-cooled and diffusion-cooled HEB mixers is not due to the cooling mechanisms but rather due to the different properties of available superconductors. The only available material for a phonon-cooled mixer with sufficiently large IF bandwidth (~ 4 GHz) is NbN, whereas a variety of clean materials (e.g., Nb, NbC, Al) are suitable for a diffusion-cooled mixer. For a readily achievable device length of $0.1 \mu\text{m}$ for example, the IF bandwidth can be ≥ 10 GHz. The requirement of low local oscillator (LO) power can also be more easily met in diffusion-cooled devices by selection of a material with lower critical temperature and low density of electron states. In contrast, the parameters in the NbN-based mixer cannot be widely varied because of the high resistivity and high transition temperature of the material and the necessity of using ultrathin films. Given the limited availability of LO power from compact solid-state sources at frequencies above 1 THz, a diffusion-cooled mixer based on aluminum is a very attractive choice for low-background radioastronomy applications.

I. INTRODUCTION

Hot-electron bolometric (HEB) superconducting mixers are becoming the desirable choice for use in radioastronomy heterodyne receivers at frequencies above 1 THz. The development effort of the last several years has resulted in the achievement of excellent device characteristics both for phonon-cooled and diffusion-cooled mixers. HEB receivers hold the low-noise record, by a wide margin, at 2.5 THz [1] and successfully compete with SIS mixers at frequencies around 1 THz.

In addition to the noise temperature, the local oscillator (LO) power and the mixer IF bandwidth are the most important characteristics which must meet certain requirements set by a specific application and/or availability of sufficiently powerful LO sources. A typical amount of LO power absorbed in the device is approximately 50-100 nW for many HEB mixers. One should account for 5-10 dB of embedding circuit and optical losses typical for terahertz mixers. While this LO requirement is lower than any competing device technology, there are nonetheless no tunable solid state sources available to pump HEB mixers at frequencies above 1.5 THz. Though an instant bandwidth of ~ 10 GHz seems to be sufficient for many practical spectroscopy applications, the unavailability of tunable THz LO sources may require much larger bandwidth for an HEB mixer. This is because a CO_2 -pumped FIR laser may be the only option for an LO, and most often the available laser emission lines are many GHz separated from the particular spectral line of interest.

Currently LO source technology is not as well developed as mixer technology and this puts further demands for improvement of HEB mixers in terms of decreasing the LO power requirements and increasing the IF bandwidth. Also,

since theoretically the HEB mixers can achieve quantum limited noise performance, it is of practical interest to find a way to achieve this limiting performance. In general, there is always a tradeoff between mixer characteristics when one attempts to optimize a particular characteristic of the mixer. The relationships between the mixer characteristics depend on the cooling mechanism dominating in the HEB device. A proper choice of the device material can create a more optimal combination of mixer parameters. In the present paper we evaluate several superconducting materials with the goal of achieving optimal mixer performance and show what limitations are set by the cooling mechanism.

II. COOLING MECHANISMS IN HEB DEVICES

Any HEB mixer device is a strip of superconducting film deposited onto a dielectric substrate between two normal-metal contacts. Depending on the device size, either phonon or diffusion cooling dominates in the thermal energy removal from a hot-electron bolometer.

The first mechanism takes place in relatively large devices with a length $L > (D\tau_{e-p})^{1/2}$ (D is the electron diffusion constant, τ_{e-p} is the electron-phonon interaction time). In this case the energy deposited into the electron subsystem by radiation or dc current is removed by means of electron-phonon collisions and consequent escape of nonequilibrium phonons into the substrate. The characteristic time of the phonon escape (proportional to the film thickness), τ_{es} , must be much shorter than the phonon-electron energy transfer time $\tau_{p-e} \approx \tau_{e-p}c_p/c_e$ (c_e , c_p are the electron and phonon specific heats respectively). At helium temperatures $\tau_{p-e} < \tau_{e-p}$ and the film must be very thin in order that all the energy will be transferred from electrons to the substrate. An intense "back and forth" exchange of energy between electrons and phonons

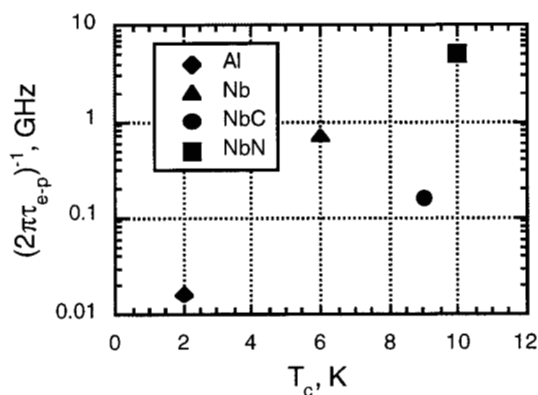


Fig. 1. Typical values of electron-phonon relaxation time for various superconducting films. The data points are shown at the critical temperatures of the materials. NbN could theoretically provide an effective bandwidth of ~ 10 GHz, however the effect of a finite phonon escape time slows down the relaxation in these films. See explanation in Section III.

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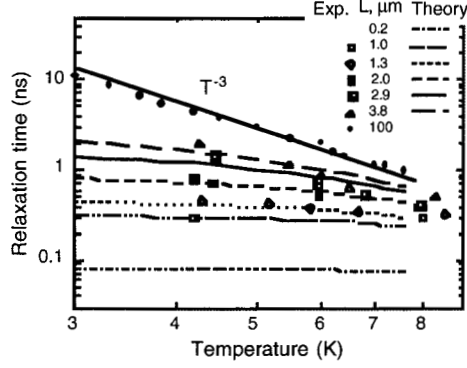


Fig. 2. The crossover from phonon cooling to diffusion cooling in NbC HEB devices of [17]. The data points following the T^{-3} law represent the electron-phonon time in a long device. The relaxation time in shorter devices has much weaker temperature dependence since the contribution of electron diffusion is larger.

will result in effective slowing down of the relaxation process, decrease of required LO power for the mixer, and increase of the noise temperature. In fact, the case when $\tau_{es} > \tau_{p-e}$ is typical for conventional low- T_c superconducting bolometers which are not used as heterodyne mixers, and for high- T_c superconducting HEB mixers (more details on the latter case can be found in [2]). For operation of the low- T_c hot electron bolometer as a mixer one should avoid this situation and make sure that $\tau_{es} \ll \tau_{p-e}$. This case was successfully implemented in Nb films with thickness $d < 10$ nm [3,4]. However, the electron-phonon time in Nb is too long to be useful for most practical applications (see Fig. 2). The same applies for many other superconducting materials. The only known material which has a sufficiently short electron-phonon time to provide the bandwidth of several GHz is NbN [5]. It will be described in greater detail in the following section.

Another cooling mechanism for HEB mixers proposed by Prober [16], uses electron diffusion in submicron size devices

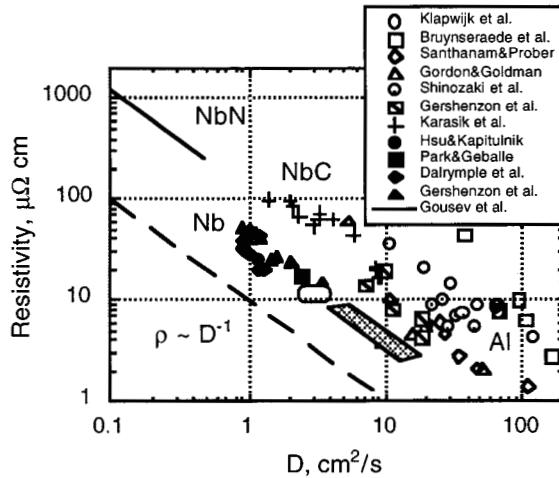


Fig. 3. The resistivity vs diffusivity data for different superconducting films. The following references were used: for Al films (open symbols) Klapwijk et al. [6], Bruynseraede et al. [7], Santhanam&Prober [8], Gordon&Goldman [9], Shinozaki et al. [10], Gershenzon et al. [11]; for NbC films Karasik et al. [17], for Nb films (closed symbols) Hsu&Kapitulnik [12], Park&Geballe [13], Dalrymple et al. [14], Gershenzon et al. [3]; for NbN films Gousev et al. [5]. The shaded tetragonal is an extrapolation for some low-resistive Nb film (diffusivity was not measured), the oval represents the range for Nb films used at JPL [15].

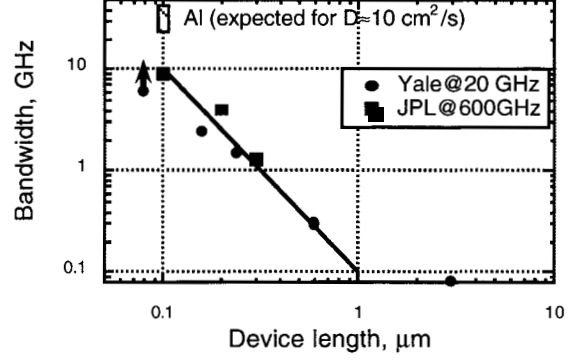


Fig. 4. The bandwidth data for Nb HEB devices fabricated at JPL [15]. The Yale data are from [18].

for fast removal of heat from the microbridge. If one assumes total absorption of nonequilibrium electrons in the normal-metal contacts, then the relaxation time is given by $\tau_{diff} = L^2/(\pi^2 D)$, where L is the device length. This expression should be strictly valid only for a normal metal bridge. In real superconducting bridges driven into the resistive state by a dc current and LO power, the resistance is distributed non-uniformly along the bridge and there is also a finite healing length in the contacts. Therefore this “lumped model” giving a functional dependence of the diffusion time on the length and diffusivity is only approximately valid, and the experimental values of τ_{diff} are often higher than predicted by this simple approximation. In general, both cooling mechanisms can coexist and the dominance of one over the other is a matter of the device size, material and temperature. Fig. 3 illustrates how the crossover from the electron-phonon to the diffusion-cooled regime occurs in NbC devices made from a film with $D \approx 10$ cm²/s [17]. For a 100-μm-long device, the electron-phonon interaction dominates at all temperatures and the relaxation time follows the T^{-3} dependence typical for clean material. For shorter devices, the temperature dependence saturates at lower temperatures where the diffusion time becomes shorter than the electron-phonon time. For very short devices, diffusion dominates and the relaxation time is temperature independent.

III. BANDWIDTH

The diffusion cooling regime can be achieved in most materials as long as the device is made sufficiently short. It is simpler to observe however when the diffusion constant $D \geq 1$ cm²/s. For smaller diffusivities, the device length needs to be less than 0.1 μm in order to provide a practical (ie: > 1 GHz) bandwidth. Such short device sizes are difficult to achieve. Fortunately, there is a variety of materials where large diffusivities can be easily obtained. As seen in Fig. 4, Nb, NbC, and Al all have $D \geq 1$ cm²/s. Many data points have been obtained for Nb microdevices with $D \approx 1$ -2 cm²/s.

The data for the devices of different length made from the same film approximately follow the expected L^{-2} as shown in Fig. 5. This dependence was previously shown at microwave frequencies below 20 GHz [18], and we show here the first confirmation at submillimeter frequencies.

For $D = 10$ cm²/s (a typical value for aluminum) and $L = 0.1$ μm, the calculated diffusion time is ≈ 1 ps which corresponds to an effective mixer bandwidth of 160 GHz. Even taking into account the difference between the theory and experiment, a bandwidth of several tens GHz seems to be quite possible.

A large range of diffusion constants gives flexibility in adjusting the mixer resistance to a desirable value. Indeed, if one tries to increase the bandwidth by using very clean film, it may happen that the resistivity will be so low that the mixer device will be mismatched with the planar antenna impedance. Such a situation is more likely in Nb which has a higher density of electron states N_e ($\rho^{-1} = N_e e^2 D$) than Al and NbC where the density of states is three times lower than in Nb (see Fig. 4). Therefore one can use cleaner films (= larger bandwidth) of these materials, while maintaining at the same time a suitable resistance for matching to rf embedding circuits. Niobium nitride is the only material which has a short enough electron-phonon time and, therefore, is useful for fabrication of HEB mixers. There is indirect evidence that the intrinsic bandwidth set by the electron-phonon relaxation time at the critical temperature of 8-9 K is ~ 10 GHz [5]. The corresponding relaxation time $\tau_{e-p} \approx 13$ ps [19] is very short and since $c_e \approx 0.3c_p$ the phonon-electron relaxation time $\tau_{p-e} \approx 40$ ps. Even for the thinnest NbN films used in the recent experiments [19,20] the phonon escape time is also 40 ps. It means that the phonons do not remove the thermal energy from the film but rather exchange it with electrons. As a result, the relaxation slows down and the apparent bandwidth is smaller than that implied by τ_{e-p} , i.e. 4 GHz instead of 10 GHz. This situation can be adequately described by introduction of both electron and phonon temperatures different from the temperature of substrate. Any further increase of bandwidth in NbN seems to be problematic because: (a) it is hardly possible to fabricate even thinner (< 3 nm) high quality NbN films; and (b) electron diffusion still does not play a role in the relaxation since $D \approx 0.2$ cm²/s.

IV. ULTIMATE NOISE PERFORMANCE AND LOCAL OSCILLATOR POWER

According to theory [21] the best HEB mixer performance takes place when the thermal fluctuation noise dominates over the Johnson noise. This is a case of a strong self-heating in the mixer device which is possible if the device has a sharp superconducting transition and large critical current density. Under these circumstances assuming that the device operates at temperature $T \ll T_c$, the SSB mixer noise temperature, T_M , is given by the following expression:

$$T_M = (n+2)T_c, \quad (1)$$

where n is the exponent in the temperature dependence of the electron temperature relaxation time. For phonon-cooled devices it is an electron-phonon time: $n = 1.6$ for NbN, $n = 2$ for Nb, $n = 3$ for NbC. For diffusion cooled devices $n = 0$. The limits given by (1) are shown in Fig. 6 (horizontal lines). One can see that the theoretical limit for Al is many times lower than that for NbN. The theory of [21] does not consider any quantum phenomena though the quantum noise limit will be important at THz frequencies. A simplistic empirical correction can be made by adding one quantum contribution, $h\nu/k_B$, to the limit of (1). As a result the difference in T_M between Al and NbN HEB mixer becomes smaller but is still significant.

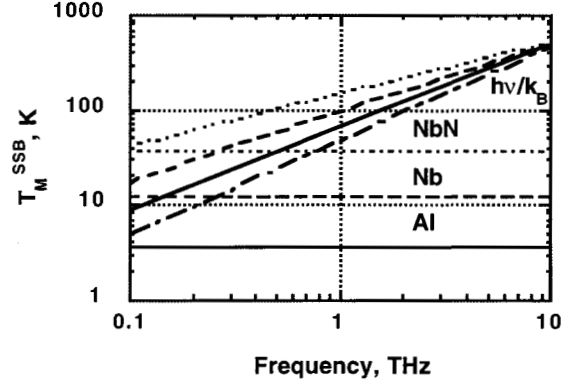


Fig. 5. Theoretical noise temperature limits for different mixer materials. The dash-and-dot line is the quantum limit.

The theory also predicts that under optimal conditions the local oscillator power should be much larger than the DC Joule power. The following equations apply in this case:

For NbN [19,22]:

$$P_{LO} = c_e(T_c) V (T_c^n - T_p^n) / [n T_c^{n-1} \tau_{e-p}(T_c)] \quad (2a)$$

$$c_e(T_c) V (T_c^n - T_p^n) / [n T_c^{n-1} \tau_{e-p}(T_c)] = c_p(T_p) / \tau_{es}(T_p - T). \quad (2b)$$

For a diffusion-cooled HEB mixer [23]:

$$P_{LO} = 4L(T_c^2 - T^2) / R, \quad (3)$$

where R is the device resistance, and L is the Lorenz constant.

The results of calculations using (2) and (3), are shown in Fig. 7. We used $R = 20 \Omega$ for diffusion-cooled Al, Nb and NbC bolometers and $V = 0.15$ (length) \times 1.5 (width) \times 0.003 (thickness) μm^3 for an NbN phonon-cooled bolometer.

A further reduction of the local oscillator power might be achieved in a phonon-cooled mixer by reduction of the volume. However, in the case of NbN, the large resistivity of the material requires the use of ~ 0.1 square size devices to ensure a reasonable match of the device resistance to a planar antenna impedance. Therefore, the NbN device of Fig. 7 is close to the optimum. In the case of diffusion-cooled mixers one has a choice of materials with lower values of critical temperature. For $T^2 \ll T_c^2$, $P_{LO} \propto T_c^2$, and one can see from Fig. 7, that Al with its low T_c (≈ 1.6 K) requires very low LO power compared to other materials. The bandwidth does not suffer however since it is temperature independent, in contrast to that in phonon-cooled devices.

V. PERFORMANCE TRADEOFFS

As can be seen from the above considerations, for a phonon-cooled HEB mixer, the IF bandwidth depends on the electron-phonon interaction time which is temperature dependent. Since a material with a relatively high T_c such as NbN is required, a wide bandwidth means higher noise temperature (1) and higher LO power (2). Thus these mixer characteristics must be traded against each other to optimize the performance for this type of mixer.

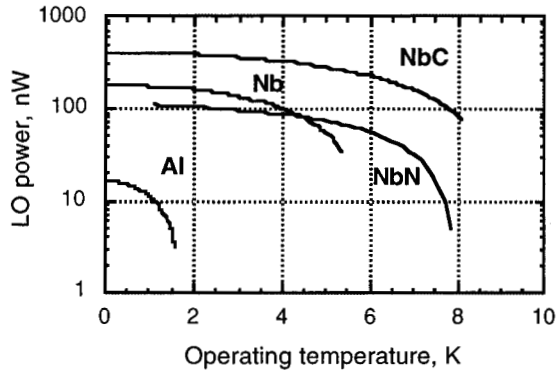


Fig. 6. Local oscillator power for optimized diffusion-cooled (Nb, NbC and Al) and phonon-cooled (NbN) HEB mixers.

For a diffusion cooled HEB mixer, the IF bandwidth is independent of temperature. Relatively lower T_C materials, such as Al, can be chosen to reduce mixer noise and LO power requirements without sacrificing IF bandwidth. This type of mixer thus provides more flexibility in optimization for a particular application.

VI. CONCLUSION

We have shown that both phonon-cooled and diffusion-cooled HEB mixers are predicted to give quantum limited noise performance. However, due to the characteristic properties of commonly used superconducting thin films, diffusion-cooled HEB provide more flexibility to meet the various needs of practical applications in regards to LO power, bandwidth, and noise. Developing HEB devices with lower critical temperature may allow the mixer to more readily reach quantum-limited noise performance at THz frequencies and meet the power requirements for the state-of-the-art tunable solid state LO sources. In particular, aluminum films appear to possess desirable and necessary qualities for optimization of HEB mixers for use in demanding radioastronomy applications.

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